Mechanical Concepts Applied in Congenital Heart Disease and Cardiac Surgery

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All biological processes are governed by principles of physics that dictate the pathophysiology and even the treatment of congenital heart diseases. In this review, basic concepts such as flow, pressure, resistance, and velocity are introduced, followed by more complex laws that describe the relationship between these variables and the disease processes. Finally, physical phenomena such as turbulence, steal and runoff phenomenon, and energy loss are discussed. By application of these principles, one can accurately quantify modifications undertaken to treat diseases, for example, the size of a patch that augments a vessel and the angle of an anastomosis to allow a certain flow.

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All biological processes are governed by the principles of physics. In congenital heart disease (CHD), these principles manifest under the constraints of native anatomic defects, leading to pathologic conditions, which often require surgical correction (Table 1). Procedures designed to repair CHD exploit the relationships between geometry and physics by attempting to correct existing anatomy to modify native physiology (Table 2). Because these interventions rely on the same physical principles as the underlying pathophysiology, understanding the physics involved is crucial in the management of CHD.

Dynamic Nature of Cardiovascular System and Hemodynamic Forces

The cardiovascular system is highly dynamic throughout life, subject to changes in response to growth and other physiologic factors. A strong relationship exists between hemodynamic forces, such as blood pressure and flow, and cardiovascular growth and remodeling [1]. An example of abnormal hemodynamics causing improper growth in the neonatal cardiovascular system is differences in growth between the aorta proximal and distal to coarctation [2].

Pediatric Heart

Compared with the adult heart, the pediatric heart has lower tolerance to ischemia, resulting in an increased propensity for significant postoperative myocardial dysfunction. The neonatal heart is also prone to myocardial edema [3], with consequences that might include decreased ventricular compliance, increased ventricular stiffness, and diastolic dysfunction.

Basic Hemodynamics—Flow, Pressure, Resistance, and Velocity

Quantification of blood flow is the most important factor in cardiovascular hemodynamics. The most basic equation that describes the flow of blood through the cardiovascular system is analogous to Ohm's law, to describe hydraulic systems. The equations for Ohm's law and its hydraulic counterpart are given below, as

$$\text{Ohm's law}: I = \frac{\Delta V}{R_e} \tag{1}$$

$$\text{Hydraulic analogy}: Q = \frac{\Delta P}{R_v} \tag{2}$$

where electrical current (I) is analogous to blood flow (Q), voltage (V) is analogous to pressure (P), and electrical resistance (R_e) is analogous to vascular resistance (R_v). For blood to flow through a vessel or across a heart valve, a pressure gradient (ΔP) must exist. For example, high blood pressure in the arterial system drives blood to flow though capillary beds to the low pressure venous system. Consequently, given a constant pressure gradient, the magnitude of blood flow through a vessel is determined by the associated resistance.

Another clinically relevant parameter frequently used to quantify cardiovascular performance is blood flow velocity (u). Increased velocity is often associated with pathology. It also creates a murmur, similar to turbulence. Moreover, blood velocity is used commonly in diagnostic evaluation of stenotic valves and vessels using continuity equation. Blood flow velocity is a

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Table 1. Congenital Heart Defects and Physical Rule Involved in Pathophysiology of Disease[a]

Defect or Disorder	Physical Rule
Anemia	Blood viscosity, velocity, turbulence
ALCAPA	Steal phenomenon
Aneurysm	Laplace; shear stress
Aortic valve regurgitation[b]	Venturi effect
Aortic/pulmonary valve stenosis	Venturi effect; velocity change (turbulence)
Atrial septal defect	Shunt due to compliance difference between ventricles; flow reversal in Eisenmenger; used as pop-off mechanism for safety
Atrioventricular canal defect	Shunt due to resistance and compliance differences between ventricles
Bicuspid aortic valve	In stenosis, same as aortic valve stenosis; in regurgitation, Venturi effect; aorta distensibility
Coarctation of the aorta	In patent ductus, flow preference due to resistance difference; Venturi effect at stenotic area; turbulence (velocity change)
Congestive heart failure	Laplace
Coronary artery fistula	Steal phenomenon; competitive flow; flow reversal
Double aortic arch	Differential flow due to difference in resistance
Double outlet right ventricle	Streamlines; shunt at VSD, difference in resistance
Eisenmenger's syndrome	Shunt direction reversal due to increased resistance in pulmonary vasculature
Endocardial fibroelastosis	Compliance change due to changes in tissue property, reduced compliance
Hypertrophic cardiomyopathy	Venturi effect, turbulence
MAPCA	Competitive flow
PAPVR	Streamlines; shunting due to resistance difference
Patent ductus arteriosus	Ductus flow depends on downstream resistance, size of duct, pressure difference; runoff phenomenon; turbulence; Venturi (small ductus)
Pulmonary hypertension	Flow reversal in shunt
RVOTO	Similar to aortic valve stenosis (Venturi)
Systolic anterior motion	Venturi effect
Subaortic stenosis	Shear stress
Tetralogy of Fallot	Similar to aortic valve stenosis (Venturi); degree of pulmonary stenosis determines shunt direction in VSD and cyanosis; difference in systemic versus pulmonary resistance used to manipulate shunt and to ameliorate cyanosis
Transposition of great arteries	Streamlines; similar to ASD and PDA; similar to VSD (if coexists); in late presentation, compliance changes
Truncus arteriosus	Differential flow in truncal artery, depends on downstream resistance (systemic versus pulmonary)
Vascular regurgitation	Venturi effect
Vascular stenosis	Diameter change, cross section
Vascular thrombosis	Shear stress, turbulence, stasis
VOTO	Venturi effect, turbulence
Ventricular septal defect	Shunt due to pressure differential between ventricles; turbulent flow across defect, creating murmur; Venturi (small defect)
Williams syndrome	Venturi effect; turbulence due to velocity change

[a] Alphabetical list. [b] In subaortic ventricular septal defect (VSD).

ALCAPA = anomalous left coronary artery from pulmonary artery; ASD = atrial septal defect; MAPCA = major aortopulmonary collateral artery; PAPVR = partially anomalous pulmonary venous return; PDA = patent ductus arteriosus; RVOTO = right ventricular outflow tract obstruction; VOTO = ventricular outflow tract obstruction.

function of both total flow and vessel size. The effective velocity ($u_{effective}$) is calculated using the following equation,

$$u_{effective} = \frac{Q}{A} \quad (3)$$

where AA is the cross-sectional area of the vessel of valve opening. Effective velocity is frequently used in clinical settings owing to its ease of calculation and approximate accuracy.

Relationship Between Physical Variables

In the cardiovascular system, the physical variables are elegantly related to each other and closely interact. The exact interaction of these parameters is described by equations and laws.

Hagen-Poiseuille Equation

The Hagen-Poiseuille equation, which essentially builds on Equation 2 by relating resistance to vessel geometry

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